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TEST OF CADMIUM SULFIDE SOLAR CELLS IN A SERIES STRING

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16. Abstract

A vacuum thermal cycling test, simulating an Earth orbit environment, was performed on nine cadmium sulfide thin-film solar cells connected in a series string. After 905 cycles, the changes in cell performance parameters were -1.9 percent in maximum power, -2.4 percent in fill factor, -3.4 percent in short-circuit current, and 3.6 percent in open-circuit voltage. A rank correlation analysis demonstrated a definite correlation between change in fill factor and change in shunt resistance.

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SUMMARY

A vacuum thermal cycling test, simulating an Earth orbit environment, was performed on nine cadmium sulfide thin-film solar cells connected in a series string. The cell string, loaded at maximum power, was subjected to 905 thermal cycles, each cycle consisting of 1 hour in air mass zero sunlight and 1/2 hour in the dark. Individual cell performance, as well as performance of the string, was measured to determine the effects of thermal cycling on the cells.

The changes in series string performance parameters and in average performance parameters of individual cells were -1.9 percent in maximum power, -2.4 percent in fill factor, -3.4 percent in short-circuit current, and 3.6 percent in open-circuit voltage. Some cells showed increased performance in maximum power and fill factor after thermal cycling, while other cells showed decreased performance. All cells had losses in short-circuit current and gains in open-circuit voltage. A rank correlation analysis demonstrated a definite correlation between change in fill factor and change in shunt resistance. Infrared pictures of cell surfaces confirmed the loss of shunt resistance in degraded cells by the presence of hot spots. An attempt was made to correlate hot-spot location with thermocouple location on the cell surface; there was no correlation between the two locations.

INTRODUCTION

The cadmium sulfide (CdS) solar cells being developed under contract to the Lewis Research Center have been subjected to vacuum thermal cycling tests in a simulated space environment to estimate cell performance in actual space environments (refs. 1 to 3). During these tests the cells have been observed to degrade in output power, fill factor, and short-circuit current with increase of cycling time. To find the causes of cell performance degradation, factors leading to cell degradation were explored in a series of tests on single cells and involved the effect of cell loading conditions and the appearance and nature of hot spots (ref. 4).

The vacuum cycling tests, until now, have been performed on individual cells. Since solar cells used in space are combined in arrays to provide the required power, it is important to know if the CdS cells will behave as individuals when interconnected or whether the interconnection will affect their behavior. Verification of the results in previous tests (ref. 4) concerning occurrence, location, and influence of shunt paths and hot spots on cell degradation is also of interest in a study of interconnected cells.

It was the purpose of this experiment to determine the performance of CdS cells connected in a series string and to investigate the effect of shunt resistance on cell performance change. Nine CdS cells were connected in series and subjected to thermal cycles in a vacuum chamber. Each cycle period was $1\frac{1}{2}$ hours, 1 hour during which the cell was illuminated by simulated air mass zero sunlight and 1/2 hour during which the cell was in the dark. The equilibrium temperature of the cells ranged from 60° C in sunlight to -120° C in the dark. Cell performance measurements were made before, during, and after vacuum thermal cycling to measure the extent of cell change. Thermograms, which are picture displays of temperature patterns on the cell surface, were also taken before and after cycling to relate cell performance with cell temperature patterns.

SYMBOLS

ΔFF	change in fill factor, percent
I	current
ΔI_{sc}	change in short-circuit current, percent
ΔP_m	change in maximum power, percent
ΔR_s	change in series resistance, percent
ΔR_{sh}	change in shunt resistance, percent
V	voltage
ΔV_{oc}	change in open-circuit voltage, percent

TEST EQUIPMENT

Ambient Test Apparatus

The ambient test apparatus was used to measure CdS cell current-voltage (I-V) characteristics and temperature coefficients prior to and following vacuum thermal cycling. The apparatus consists of a temperature-controlled block with provisions for cell vacuum holddown and temperature variation, a tungsten iodide light source filtered through 1 gram per liter (1 g/1000 cu cm) copper sulfate solution, an electronic load which varies the load across the cell from open-circuit voltage to short-circuit current, and an x, y-plotter which records the I-V curve. The light intensity at the control block surface is maintained at air mass zero intensity using a CdS, airplane flown, standard cell (ref. 5). The intensity is reproducible to ±0.3 percent of 1 solar constant, and the light uniformity over the test plane is ±2 percent. The standard deviations of open-circuit voltage, short-circuit current, and maximum power are ±1.3 millivolts, ±2.1 milliamperes, and ±2.8 milliwatts, respectively (ref. 6).

Vacuum Chamber

A 2- by 4-foot (0.61- by 1.22-m) vacuum chamber having liquid-nitrogen-cooled walls capable of maintaining a vacuum of 1×10^{-8} torr (ref. 7) was used for vacuum thermal cycling tests. The liquid-nitrogen-cooled walls maintain solar-cell temperatures at about 60° C (333 K) when illuminated with air mass zero simulated sunlight. When a shutter is interposed between simulator and vacuum chamber window, the solar-cell temperature drops to -120° C.

Solar Simulator

A xenon lamp solar simulator capable of running continuously for hundreds of hours was used to maintain air mass zero sunlight intensity on the CdS cells during vacuum thermal cycling. The simulator illuminates a 12- by 12-inch (0.3- by 0.3-m) square area at the CdS cell test plane in the vacuum chamber. The uniformity of intensity over this area was measured to be within ±3 percent of air mass zero intensity.

Cell Mounting Fixture

The cell mounting board is shown in figure 1. The cells are attached to each other and to the 1/8-inch- (0.32-cm-) thick glass epoxy board by 1-mil- (25.4-μm-) thick Kapton tape. Four electrical lead wires (no. 22) were soldered to each cell, two wires to measure cell voltage and two to carry cell current. In addition, copper-clad Kapton was soldered to tabs of adjoining CdS cells to form the series string. Thermocouples on the back sides of the CdS cells were used to monitor cell temperatures. Welded copper-constantan wires (40 gage) were attached to the back of each cell with a 1-square-centimeter piece of Kapton tape (fig. 2). A small amount of thermal conducting compound was applied between thermocouple and cell to assure good thermal contact.

Two silicon cells were attached to the mounting board. These cells were used to set the intensity of the solar simulator beam at the test plane and to provide a continuous monitor of the light intensity during thermal cycling.

Infrared Viewing Device

The instrument used to view temperature changes on the cell surface is shown in figure 3. The camera captures the infrared rays emitted by the object and electronically produces an image of the object on a display unit. A photograph of the image on the display, called a thermogram, is obtained using a photographic camera for a permanent record of the image. Further information on the operation and properties of the device is given in reference 8.

TEST PROCEDURE

The cells selected for cycling tests were obtained from a group of 75 cells delivered to the Lewis Research Center in January 1969. All 75 cells met quality control specifications required for production line CdS cells delivered under contract to Lewis. Their minimum electrical performance standards at air mass zero, 25° C conditions were 2.8 percent for efficiency and 0.685 for fill factor. The selection process involved taking cells for test with efficiencies equal to the average efficiency of the entire group as measured and delivered by the manufacturer.

The cells were then tested for hot spots. Thermograms of the cells were obtained using the dark forward bias techniques described in reference 4. The application of dark forward currents was brief (up to 0.4 A for less than 1/2 min on each cell) so as not to degrade the cell. One cell (5) instantly showed a hot spot, while another (8) had a suspected hot region. Liquid crystals were later applied to these cells. The hot spot on cell 5 was accurately located and marked for application of thermocouples. The hot region in cell 8 could not be pinpointed, so the center of the region was marked for thermocouple application.

Current-voltage characteristics of the cells were measured on the ambient test apparatus at 25°, 40°, 50°, and 60° C. Temperature coefficients for open-circuit voltage and maximum power were calculated from these data so that temperature corrections during cycling could be made. The I-V characteristics were also measured for use as the basic measurement of cell performance prior to testing; I-V characteristics measured after testing could then be compared with pretest measurements to study cell performance changes due to thermal cycling.

The nine cells were then mounted on the epoxy board holder and connected in series. Electrical leads and thermocouples were next applied so that the I-V characteristics of the individual cells, as well as the characteristics of the series string, could be measured. In earlier tests it appeared that certain hot regions on the cell might correlate with thermocouple location. Therefore, the thermocouple locations on the back side of the cell were selected in an irregular pattern to determine if thermocouple location could be correlated with location of hot spots which were expected to appear during cycling. The two pretest hot spot regions on cells 8 and 5 had thermocouples applied to them.

The cells were placed in the vacuum chamber, and thermal cycling tests were started. The string was loaded at the maximum power point during the first cycle and was maintained at that load for 905 cycles. Cell I-V characteristics, as well as those of the whole string, were measured about every 50 cycles. At the end of the test, the cells were taken out of the chamber and measured on the ambient test apparatus within 1 hour after cycle 905. The measurements were performed at 50° C because of a gradual drift downward in temperature (57° to 50° C) of the cells during vacuum thermal cycling. Several hours later I-V characteristics of the cells were again measured on the ambient test apparatus at temperatures of 25°, 40°, 50°, and 60° C. Finally, the cells were placed in a dark box and dark forward bias currents at 0.4 ampere were applied for 10 seconds. At the end of 10 seconds, thermograms of the biased cells were taken.

RESULTS AND DISCUSSION

Curves of relative values of maximum power, fill factor, open-circuit voltage, and short-circuit current against cycles are plotted for the series string in figure 4. Comparison of series string performance with the performance of the nine individual cells showed no substantial differences. For example, the maximum power of the string was within 1.5 percent of the summed maximum power of the individual cells during the cycle. Similarly, fill factor, open-circuit voltage, and short-circuit current performance measurements of the string were, within experimental precision (±1.5 percent), the same as the performance calculated from the individual cell data. Thus, the interconnection of the solar cells in series demonstrates no measurable effect on the I-V characteristics of the string when compared with the I-V characteristics of the nine individual cells measured independently of each other.

The changes in performance parameters of the cell group as measured by the ambient test apparatus are presented at the right in figure 4. Here again, the differences in performance between the series string and the averages of the cell group do not differ substantially. The average changes for maximum power, fill factor, open-circuit voltage, and short-circuit current were -1.9, -2.4, 3.6, and -3.4 percent, respectively. As shown in figure 4, the greatest measured difference between in situ cycling data and ambient tester data is 3.4 percent for short-circuit current. At present, there is no explanation for the difference.

The changes in performance parameters after this test were compared with results obtained for seven cells tested by another laboratory (ref. 3). These cells, manufactured in March 1968 and tested as individuals, had undergone 2031 vacuum thermal cycles under conditions almost identical to those sustained by the nine cell series string. Similarly, the seven cells were measured before, during, and after cycling. These results show that, at cycle 940, the average maximum power loss for the group of seven cells was 12 percent, compared with 1.9 percent for the nine-cell group. Likewise, the fill-factor loss for the group of seven cells was 6 percent; the nine-cell series string had only lost 2.4 percent in fill factor. Finally, the short-circuit current loss was 10 percent for the seven-cell group and only 3.4 percent for the nine-cell string. The only comparable results between the two tests occurred for the open-circuit voltage, which increased for both groups by 3 to 4 percent. Thus, the comparison of the two separate cell groups for the first 940 cycles indicates that the nine-cell series string had undergone considerably less degradation than did the seven-cell group.

The effect of vacuum thermal cycling on the individual cells is shown in tables I and II. The results listed are for the set of measurements at 50° C taken within 1 hour after shutdown of cycle 905. The positions of the cells in table II are the same as those of the cells during vacuum thermal cycling.

All cells showed a rise in open-circuit voltage during cycling. The measurements on the ambient test apparatus confirmed the in-tank data. Cell open-circuit voltage increases ranged from 1.9 to 4.9 percent. A check of the instruments and measurement of two control cells showed that the increases in open-circuit voltage of the cycled cells were not a result of measurement error. Consideration was given to the possibility that the increases were related to the interconnection of cells into a series string. However, cycling tests performed on single cells by another laboratory also revealed open-circuit voltage increases with time (ref. 3).

All cells showed a decrease in short-circuit current after testing. The range of ΔI_{sc} was from -1.5 to -5.3 percent. Two cells, 6 and 7, delaminated in the CdS layer along the edge. The cell with greatest delamination also had the largest short-circuit current loss (5.3 percent). In this cell, the area of delamination was measured to be 2.9 percent of the total active solar-cell area. The other delaminated cell had only a 0.5-percent area loss and had a short-circuit current loss of 4.6 percent.

The percentage change in fill factor was plotted against the percentage change in maximum power (fig. 5). In this plot the changes in maximum power for cells 6 and 7 have been adjusted to account for the area loss in short-circuit current due to delamination. As shown in reference 9, the percentage loss in short-circuit current and maximum power as a result of delamination is directly proportional to the delaminated area; the fill factor, on the other hand, remains unaffected. Thus, after adjustment due to delamination, figure 5 illustrates a roughly linear correlation between maximum power and fill factor. This curve is indicative of changes in series and shunt resistances since changes in either of these parameters will affect the fill factor as well as the maximum power.

In order to further investigate the effects of the resistance on the degradation, the results for fill factor listed in table I were rearranged in order of increasing degradation in table III.

The percentage changes in shunt resistance and series resistance are also shown in table III. A Kendall rank correlation analysis (ref. 10) was performed to test the hypothesis of independence between fill factor and shunt resistance. The analysis yielded a correlation coefficient of $\tau = 0.78$, which corresponds to an α error of about 0.001. Thus, the probability of an error is less than 1 percent in stating that change in shunt resistance was a cause of change in fill factor in this experiment. The correlation analysis to test the hypothesis of independence between change in fill factor and change in series resistance gave a correlation coefficient of $\tau = 0.28$. In this test, then, the change in series resistance did not correlate strongly with the change in fill factor. Excluding the effects of changes in series resistance, a Kendall partial rank correlation coefficient τ turned out to be about 0.79, a somewhat better correlation between changes in fill factor and changes in shunt resistance. Details of this analysis are given in the appendix.

Thermograms of the CdS cells taken after testing are also shown in table III and confirm, at least qualitatively, that shunt resistance is influencing the amount of degradation. During application of dark forward bias voltage the power passing through the cell is dissipated as heat. The infrared radiation emitted by the cell is collected by the infrared viewing device and imaged electronically on the display unit. Cells which dissipate power uniformly are displayed as uniform images on the thermogram. On the other hand, cells with discontinuities, such as low shunt resistance paths, dissipate the applied power nonuniformly and consequently give rise to thermograms showing temperature gradients and hot spots. An estimate of the temperature differences on the cell surface is obtained by comparing the image with the gray scale shown at the bottom of each thermogram. The thermograms in table III were taken with a temperature difference of 5° C from black to white on the scale. Thus, cells which show a uniform shade have essentially 0° C difference in temperature over their surface. Cells which have shades from black to white can have at least a 5° C difference between areas of the cell. The first three cells in table III had little or no degradation in fill factor and shunt resistance; their thermograms also demonstrate a fairly uniform temperature. On the other hand, the three cells with greatest degradation had hot spots. The cells which had degradations intermediate to these also showed hot spots, but not as severe as those in cells with greatest degradation.

The cell with greatest maximum power degradation was cell 5. As mentioned earlier, a precycling search for hot spots indicated a positive hot spot on cell 5 and a possible hot spot on cell 8. Post-test thermograms of these cells showed the hot spot on cell 5 remained in the original position, whereas the hot spot on cell 8 did not. Since the original hot spot on cell 8 was difficult to locate prior to cycling, it is possible that the spot may not have been accurately located prior to cycling.

During cycling the thermocouple applied to the hot spot on cell 5 registered 1° to 3° C higher than the other thermocouple on the cell back surface. These differential temperature readings between thermocouples did not increase by more than 2° C between cycles 1 and 905. Therefore, no positive evidence was obtained in this test to indicate that the hot spot, and thus the shunt resistance, was changing very greatly during vacuum thermal cycling.

The locations of hot spots and thermocouples on each cell were compared. In figure 6, the cells are drawn with appropriate locations as obtained from figure 2 (for thermocouples) and table III (for hot spots). As shown in the figure the hot spots generally occurred along the outer edges of the active cell area. With the exception of cell 5, there were no hot spots found in the vicinity of a thermocouple. And as mentioned earlier, this thermocouple was purposely placed at this hot spot, which was located prior to testing of the cell. Thus, there appears to be no correlation between application of thermocouples and the occurrence of hot spots.

SUMMARY OF RESULTS

Nine cadmium sulfide solar cells, connected in series and loaded at their maximum power point, were subjected to a total of 905 vacuum thermal cycles. The results of these tests showed that

1. There was no significant difference between the I-V characteristic of the series string and the characteristic calculated from the I-V curves of the nine cells measured individually.

2. All nine cells increased in open-circuit voltage. The average gain in open-circuit voltage was 3.6 percent.

3. The average loss in short-circuit current was 3.4 percent, with a range of 1.5 to 5.3 percent. Two cells, which showed greatest degradation in short-circuit current, delaminated; the percentages of delaminated area relative to active cell area were 0.5 and 2.9 percent. The percentage losses in short-circuit current for these cells were 4.6 and 5.3 percent, respectively.

4. The average loss in maximum power was 1.9 percent. One cell showed a significant gain in power (4.1 percent), some showed no change, and others had losses up to 7.4 percent.

5. The average change in fill factor was -2.4 percent. The range in fill-factor performance change after testing was 1.8 to -6.2 percent.

6. A Kendall rank correlation analysis of fill factor and shunt resistance demonstrated a definite correlation between change in fill factor and change in shunt resistance. The coefficient was calculated to be 0.78, which indicated the probability of an error is less than 1 percent in stating that change in shunt resistance was a cause of change in fill factor.

7. Thermograms of cells with losses in fill factor revealed hot spots on the cell surface; thermograms of three cells with no loss in fill factor showed a uniform thermal distribution across the cell surface and the absence of hot spots.

8. Six of the nine cells were found to have hot spots after testing. Although these cells were loaded at maximum power most of the time, they were intermittently unloaded to measure I-V characteristics. It has not been established in this test when these hot spots were formed.

9. There was no correlation between hot-spot location and thermocouple location.

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National Aeronautics and Space Administration,
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120-33.

APPENDIX - KENDALL RANK CORRELATION ANALYSIS

The Kendall rank correlation coefficient τ was computed from the equation

$$\tau_{xy} = \frac{\sum_{i}^{N} S_i}{\frac{1}{2} N(N - 1)}$$

where N is the number of objects ranked in pairs of X_i and Y_i, and S_i is the difference between the number of ranks higher and the number of ranks lower than a given rank position of Y_i under the conditions that (1) X is arranged in natural order from $1 \rightarrow N$ and (2) ranks being considered are those only to the right of rank Y_i. In table III the ΔFF and ΔR_{SH} for the nine cells were arranged in the following manner:

	Cell								
	3	7	9	6	8	4	1	5	2
$\Delta FF \rightarrow X$, percent	1.8	1.0	0	-1.3	-2.0	-3.8	-5.4	-5.8	-6.2
$\Delta R_{SH} \rightarrow Y$, percent	24	19	-4	-27	-50	-18	-22	-63	-76

Then, according to ranks,

	Cell								
	3	7	9	6	8	4	1	5	2
Rank → X	1	2	3	4	5	6	7	8	9
Rank → Y	1	2	3	6	7	4	5	8	9

Therefore,

$$\tau_{xy} = \frac{S}{\frac{1}{2}(N)(N - 1)} = \frac{(8 - 0) + (7 - 0) + (6 - 0) + (3 - 2) + (2 - 2) + (3 - 0) + (2 - 0) + (1 - 0)}{\frac{1}{2}(9)(9 - 1)}$$

$$= \frac{28}{36} = 0.78$$

The value $\tau_{xy} = 0.78$ corresponds to a $\Pr(\tau \geq 0.78) = 0.0012$ (ref. 10).

The equation to partial out the effect of series resistance changes in the correlation between ΔFF and ΔR_{SH} is

$$\tau_{xy \cdot z} = \frac{\tau_{xy} - \tau_{zy}\tau_{zx}}{\sqrt{\left(1 - \tau_{zy}^2\right)\left(1 - \tau_{zx}^2\right)}}$$

where z is the set related to series resistance changes. The cell arrangement is then

	Cell								
	3	7	9	6	8	4	1	5	2
ΔFF - X, percent	1.8	1.0	0	-1.3	-2.0	-3.8	-5.4	-5.8	-6.2
Rank - X	1	2	3	4	5	6	7	8	9
ΔR_{SH} - Y, percent	24	19	-4	-27	-50	-18	-22	-63	-76
Rank - Y	1	2	3	6	7	4	5	8	9
ΔR_s - Z, percent	4	15	3	14	0	26	27	12	16
Rank - Z	3	6	2	5	1	8	9	4	7

Therefore,

$$\tau_{zx} = \frac{(6 - 2) + (3 - 4) + (5 - 1) + (3 - 2) + (4 - 0) + (1 - 2) + (0 - 2) + (1 - 0)}{\frac{1}{2}(9)(8)} = 0.28$$

$$\tau_{zy} = \frac{(6 - 2) + (3 - 4) + (5 - 1) + (1 - 4) + (0 - 4) + (1 - 2) + (2 - 0) + (1 - 0)}{\frac{1}{2}(9)(8)} = 0.056$$

and

$$r_{xy \cdot z} = \frac{0.78 - (0.056)(0.28)}{\sqrt{(1 - 0.056^2)(1 - 0.28^2)}} = 0.79$$

The effect of partialling out the series resistance is to increase the correlation between ΔFF and ΔR_{SH} to some extent.

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TABLE I. - ABSOLUTE VALUES OF CELL PERFORMANCE CHARACTERISTICS BEFORE AND AFTER VACUUM THERMAL CYCLING

[All data taken in air at 50° C (323 K) under simulated air mass zero sunlight.]

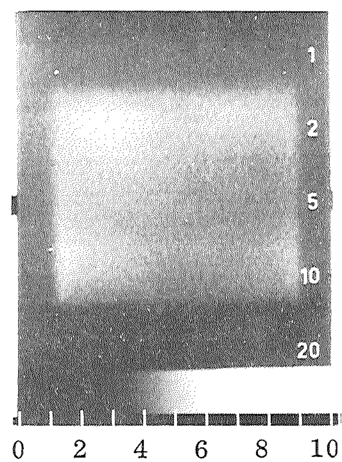
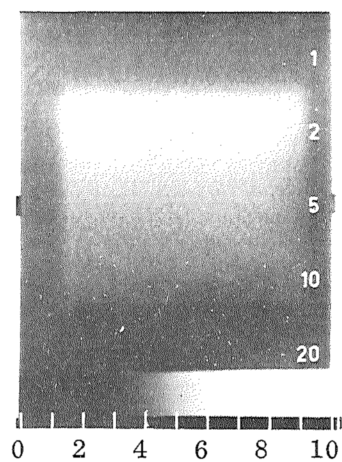
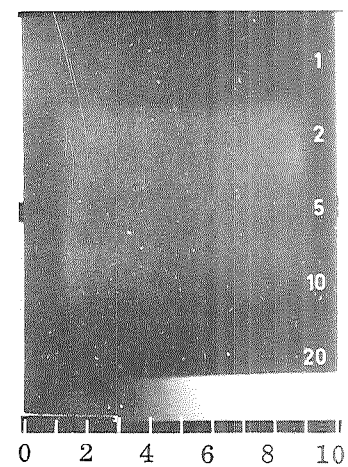
Cell	Fill factor		Maximum power, W		Short-circuit current, A		Open-circuit voltage, V	
	Before	After	Before	After	Before	After	Before	After
1	0.643	0.608	0.209	0.201	0.760	0.736	0.428	0.448
2	.675	.633	.221	.213	.785	.773	.417	.433
3	.674	.686	.217	.226	.785	.761	.411	.431
4	.640	.616	.204	.200	.744	.721	.428	.449
5	.668	.629	.229	.212	.799	.765	.430	.438
6	.676	.667	.218	.215	.765	.730	.421	.438
7	.689	.696	.220	.220	.760	.720	.421	.437
8	.686	.672	.229	.224	.781	.760	.429	.439
9	.691	.691	.228	.226	.775	.748	.425	.436

TABLE II. - PERCENTAGE CHANGE IN OPEN-CIRCUIT VOLTAGE V_{oc}, SHORT-CIRCUIT CURRENT I_{sc}, MAXIMUM POWER P_m, AND FILL FACTOR FF DUE TO THERMAL CYCLING

[Cell arrangement corresponds to that in fig. 1; all data taken in air at 50° C (323 K) under simulated air mass zero sunlight.]

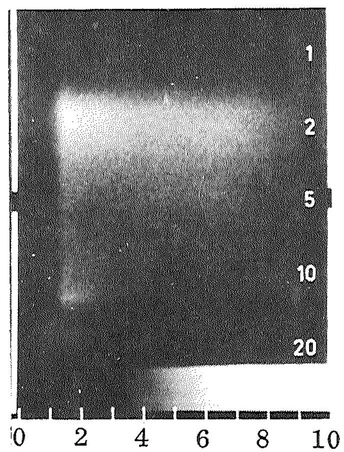
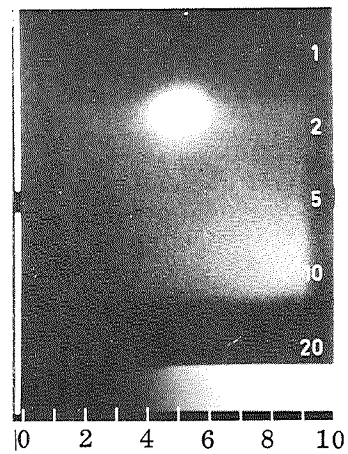
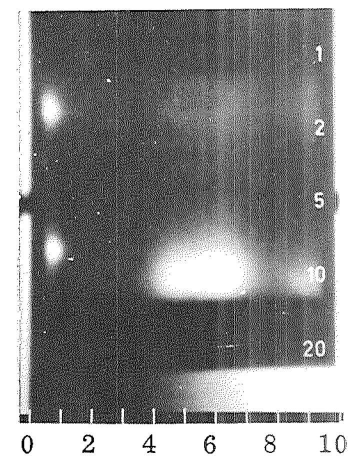
	Cell 1	Cell 6	Cell 7
ΔV_{oc}	4.7	4.0	3.8
ΔI_{sc}	-3.2	-4.6	-5.3
ΔP_m	-3.8	-1.4	.0
ΔFF	-5.4	-1.3	1.0
	Cell 2	Cell 5	Cell 8
ΔV_{oc}	3.8	1.9	2.3
ΔI_{sc}	-1.5	-4.3	-2.7
ΔP_m	-3.6	-7.4	-2.2
ΔFF	-6.2	-5.8	-2.0
	Cell 3	Cell 4	Cell 9
ΔV_{oc}	4.9	4.9	2.6
ΔI_{sc}	-3.1	-3.1	-3.5
ΔP_m	4.1	-2.0	-0.9
ΔFF	1.8	-3.8	.0

TABLE III. - THERMOGRAMS AND ELECTRICAL PARAMETERS OF CELLS

	Cell		
	3	7	9
Thermogram[a]			
Change in fill factor, ΔFF, percent	1.8	1.0	0
Change in shunt resistance, ΔR_{sh}, percent	24	19	-4
Change in series resistance, ΔR_s, percent	4	15	3

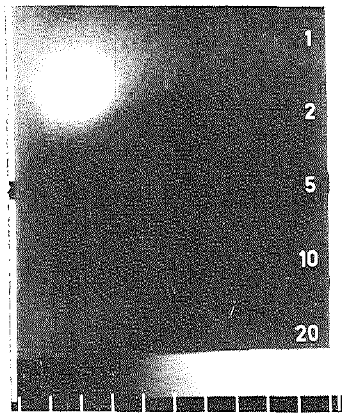
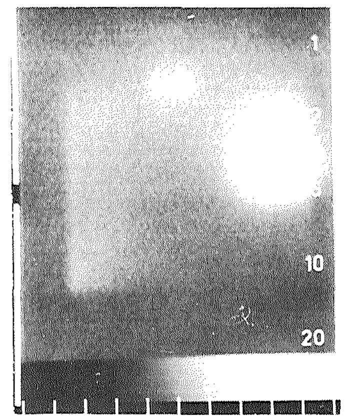
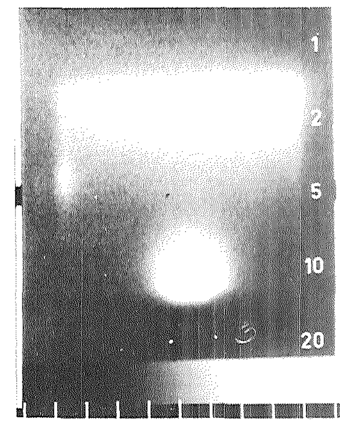
[a]Temperature scale, change from black to white represents 5° C. View is of cell front surface with positive lead on top.

TABLE III. - Continued. THERMOGRAMS AND ELECTRICAL PARAMETERS OF CELLS

	Cell		
	6	8	4
Thermogram[a]			
Change in fill factor, ΔFF, percent	-1.3	-2.0	-3.8
Change in shunt resistance, ΔR_{sh}, percent	-27	-50	-18
Change in series resistance, ΔR_s, percent	14	0	26

[a]Temperature scale, change from black to white represents 5° C. View is of cell front surface with positive lead on top.

TABLE III. - Concluded. THERMOGRAMS AND ELECTRICAL PARAMETERS OF CELLS

	Cell		
	1	5	2
Thermogram[a]			
Change in fill factor, ΔFF, percent	-5.4	-5.8	-6.2
Change in shunt resistance, ΔR_{sh}, percent	-22	-63	-76
Change in series resistance, ΔR_s, percent	27	12	16

[a]Temperature scale, change from black to white represents 5° C. View is of cell front surface with positive lead on top.

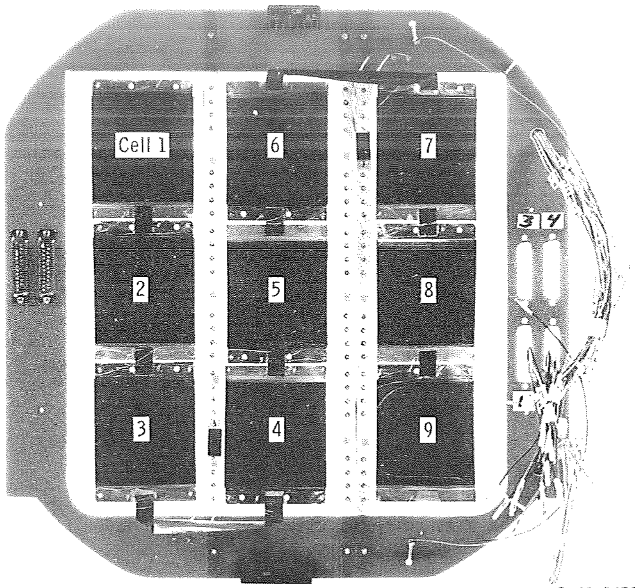


Figure 1. - Front view of CdS solar cells on vacuum thermal cycling mounting board.

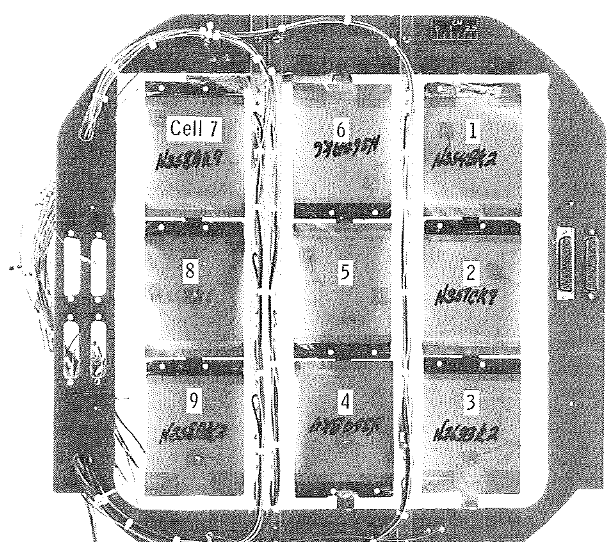


Figure 2. - Back view of CdS solar cells on mounting board with thermocouples attached.

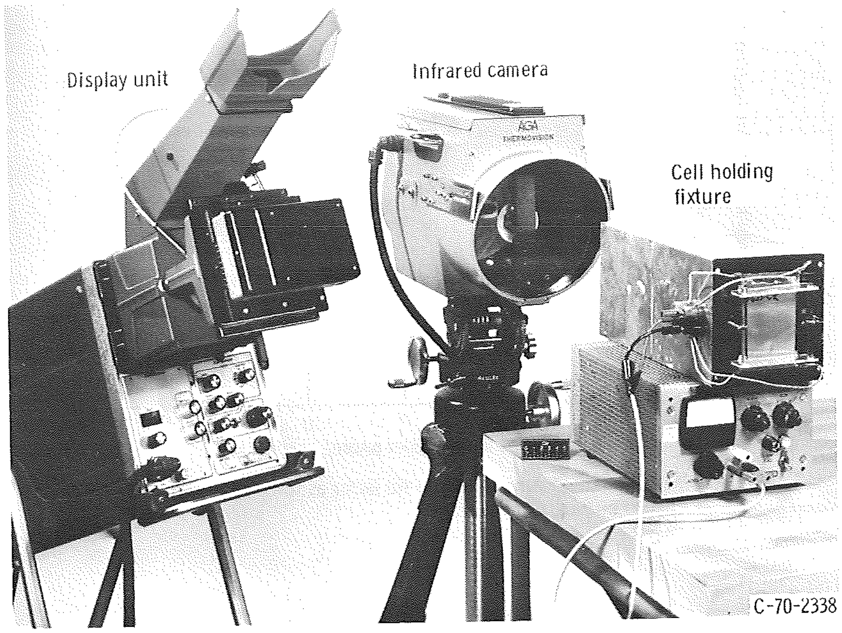


Figure 3. - Infrared viewing device.

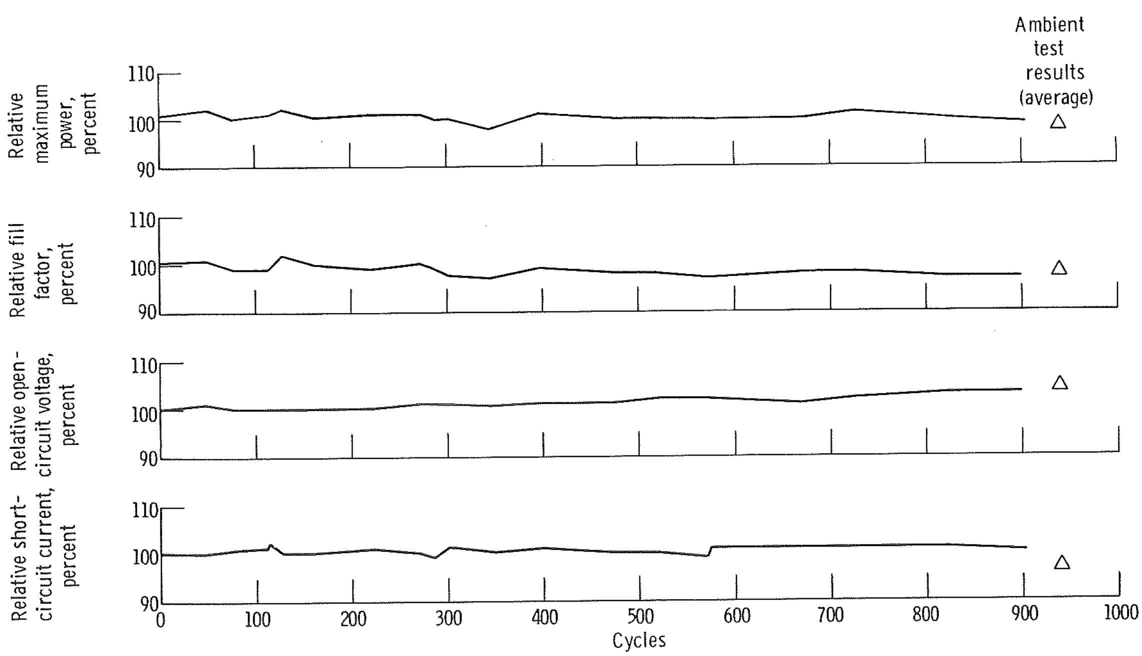


Figure 4. - Relative performance parameters as function of number of cycles.

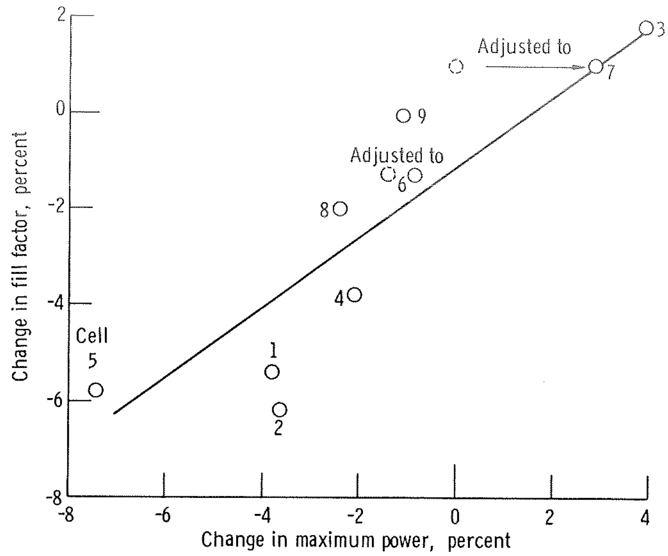


Figure 5. - Percentage change in fill factor as function of percentage change in maximum power.

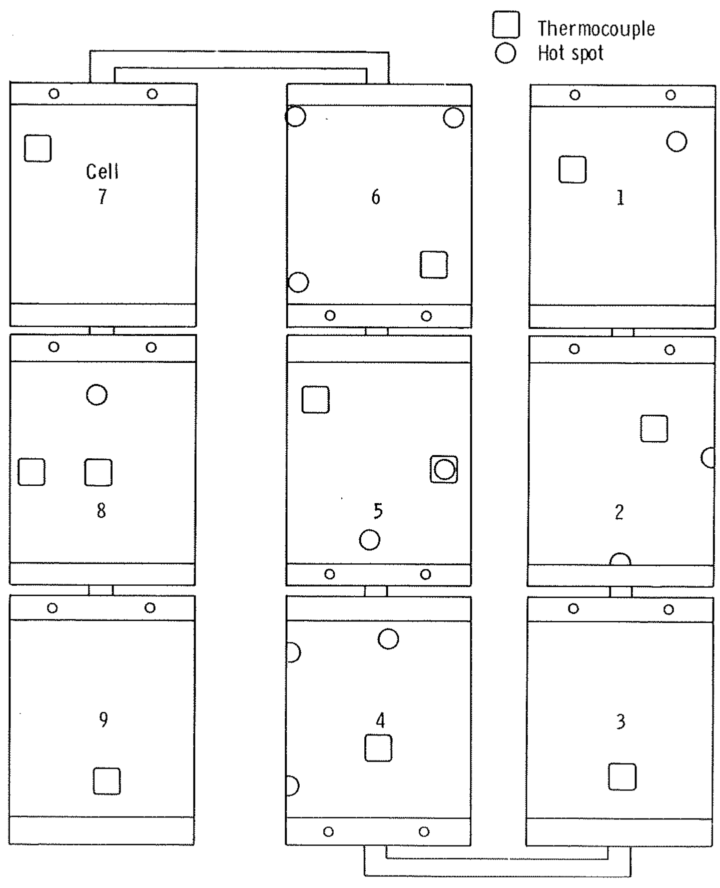


Figure 6. - Location of hot spots and thermocouples. Back view.

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